

PHOTOABSORPTION ON NUCLEI

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We calculate the total photoabsorption cross section and cross sections for inclusive pion and eta photoproduction in nuclei in the energy range from 300 MeV to 1 GeV within the framework of a semi-classical BUU transport model. Besides medium modifications like Fermi motion and Pauli blocking we focus on the collision broadening of the involved resonances. The resonance contributions to the elementary cross section are fixed by fits to partial wave amplitudes of pion photoproduction. The cross sections for $NR \rightarrow NN$, needed for the calculation of collision broadening, are obtained by detailed balance from a fit to $NN \rightarrow NN\pi$ cross sections. We show that a reasonable collision broadening is not able to explain the experimentally observed disappearance of the $D_{13}(1520)$ -resonance in the photoabsorption cross section on nuclei.

1 Introduction

The total nuclear photoabsorption cross section in the first and second nucleon resonance region which was recently measured in Mainz¹ and Frascati^{2,3,4} shows clear medium modifications compared to the elementary cross section on the proton and deuteron^{5,6,7}. One observes a strong broadening of the Δ -peak and the disappearance of the higher resonances D_{13} and F_{15} while the total cross section per nucleon is almost independent of the mass of the nucleus.

We present now a consistent calculation of the photon-nucleus reaction over the whole energy range from 300 MeV to 1 GeV within the framework of a semi-classical BUU transport model^{8,9} which has been very successfully applied to the description of heavy-ion collisions up to bombarding energies of 2 GeV/A^{10,11} and pion-nucleus reactions¹². Our calculation is based on the assumption that the total photonuclear cross section is the incoherent sum of contributions from all nucleons where we neglect possible shadowing effects. Besides more or less trivial medium modifications like Fermi motion and Pauli blocking we investigate the effect of collision broadening for the involved resonances. This may lead to a better understanding of the behaviour of nucleon resonances in nuclear matter.

Pion photoproduction on nuclei is determined both by the elementary (γ, π) process on the nucleon as well as by final state π -N interactions whereas photoabsorption is dominated by the former reaction. A detailed investigation of (γ, π) on nuclei could thus help to separate these two effects and to identify

true in-medium effects on the primary production process.

In section 2 we start with a brief presentation of the used BUU model. The results for the collision widths of the nucleon resonances within this model are shown in section 3¹³. The elementary photoabsorption cross section on the nucleon is discussed in section 4. Finally we present our results for the total photoabsorption cross section on nuclei (section 5.1)¹³ and the photoproduction of pions (section 5.2) and etas (section 5.3)¹⁴.

2 The BUU model

The BUU equation^{8,9} describes the classical time evolution of a many-particle system under the influence of a self-consistent mean field potential and a collision term. For the case of identical particles it is given by:

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m} \frac{\partial f}{\partial \vec{r}} - \vec{\nabla} U \frac{\partial f}{\partial \vec{p}} = I_{coll}[f] \quad , \quad (1)$$

where $f(\vec{r}, \vec{p}, t)$ stands for the one-particle phasespace density, $U[f]$ denotes the self-consistent mean field potential and $I_{coll}[f]$ is the collision term which - for a fermionic system - respects the Pauli principle. For the description of a system of non-identical particles one gets an equation for each particle species that is coupled to all others by the collision integral or the mean field potential. Besides the nucleon we take all baryonic resonances up to a mass of 2 GeV as well as the pion, the eta- and the rho-meson into account.

The collision term allows for the following reactions:

$$\begin{aligned} N N &\rightarrow N N \\ N N &\leftrightarrow N R \\ N N &\leftrightarrow N N \pi \quad (\text{S - wave}) \\ N R &\rightarrow N R' \\ R &\leftrightarrow N m \\ R &\leftrightarrow N \pi \pi \\ &\leftrightarrow \Delta(1232) \pi, N(1440) \pi, N \rho, N \sigma \\ \pi \pi &\leftrightarrow \rho, \sigma \quad , \end{aligned}$$

where R stands for a baryonic resonance and m for a meson^{13,11}.

3 Collision broadening

We have used the cross sections for the interaction of resonances with nucleons from our transport model to calculate the collision widths¹⁵ of the resonances

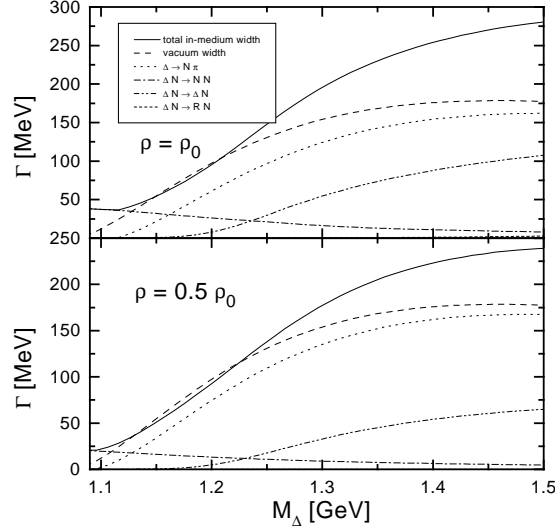


Figure 1: In-medium width of the $\Delta(1232)$.

that are important for photonuclear reactions¹³. These are the $P_{33}(1232)$, the $D_{13}(1520)$ and the $F_{15}(1680)$. The $S_{11}(1535)$ is important for the calculation of etaproducts.

Since nucleon final states coming from spontaneous decays of resonances can be Pauli blocked in the nuclear medium there is also a reduction of the width. The total in-medium width is therefore:

$$\Gamma_{tot}^{med} = \Gamma_{spon}^{med} + \Gamma_{coll}^{med} \quad , \quad (2)$$

where Γ_{spon}^{med} stands for the sum of the one-pion-, two-pion- and eta-width.

In figure 1 we show the different contributions to the in-medium width of the $\Delta(1232)$ at nucleon densities ρ_0 and $\rho_0/2$ in isospin symmetric nuclear matter. Here the momentum of the resonance is related to its mass by the requirement that the resonance was created by photoabsorption on a free nucleon at rest. For comparison the vacuum width is also shown.

At ρ_0 the collision width coming from resonance absorption $N \Delta \rightarrow N N$ is at the pole of the resonance ($M=1.232$ GeV) about 25 MeV. This partial width decreases with increasing mass. The contribution from $N \Delta \rightarrow N \Delta$ has - averaged over the mass distribution - about the same size as the one from $N \Delta \rightarrow N N$. However, here we get a strong increase of $\Gamma_{N\Delta \rightarrow N\Delta}$ with

increasing mass because of the phase space weighted integral over the mass distribution of the outgoing Δ -resonance.

In the region of the resonance pole the total in-medium width is almost independent of the nucleon density since collision broadening and Pauli reduction of the free width nearly compensate. Thus, at the resonance pole the net broadening compared to the vacuum width is very small; at about 100 MeV above the pole the width has grown by about 50 MeV, mainly due to the $N \Delta \rightarrow N \Delta$ scattering process.

In figure 2 the in-medium widths of the $N(1520)$, the $N(1535)$ and the $N(1680)$ are compared with the vacuum widths and split up into their partial widths. In all cases the collision widths at the poles of the resonances are only of the order 20 - 40 MeV which leads to a small net broadening because the Pauli blocking of the free width is less important than in the case of the Δ -resonance. A collision width of 300 MeV^{16,15} for the $D_{13}(1520)$ seems to be far from being realistic.

4 The total photoabsorption cross section on the nucleon

For the one-pion production cross section we use partial-wave amplitudes¹⁷ and fit the contributions coming from the $P_{33}(1232)$, $D_{13}(1520)$, $S_{11}(1535)$ and $F_{15}(1680)$ resonances to these amplitudes because - especially in the region of the Δ -resonance - interference terms with the background are quite important¹⁴. An incoherent decomposition of the total photoabsorption cross section into resonance and background contributions as done by Kondratyuk et al.¹⁵ should not be used if one wants to investigate possible modifications of the resonance contributions in nuclei.

While the one-pion production cross sections can nicely be decomposed into Breit-Wigner type resonance contributions and a smooth background, the structure of the two-pion production cross sections is not described by the resonance contributions that are induced by the two-pion decay widths of the resonances¹⁴. The difference between the experimental cross section and the Breit-Wigner type resonance contributions is treated as background, where the momenta of the outgoing particles are distributed according to three-body phase space. Therefore the only medium modification is the possible Pauli blocking of the outgoing nucleon.

4.1 Medium modifications

We use the following medium modifications for the elementary photon-nucleon cross section:

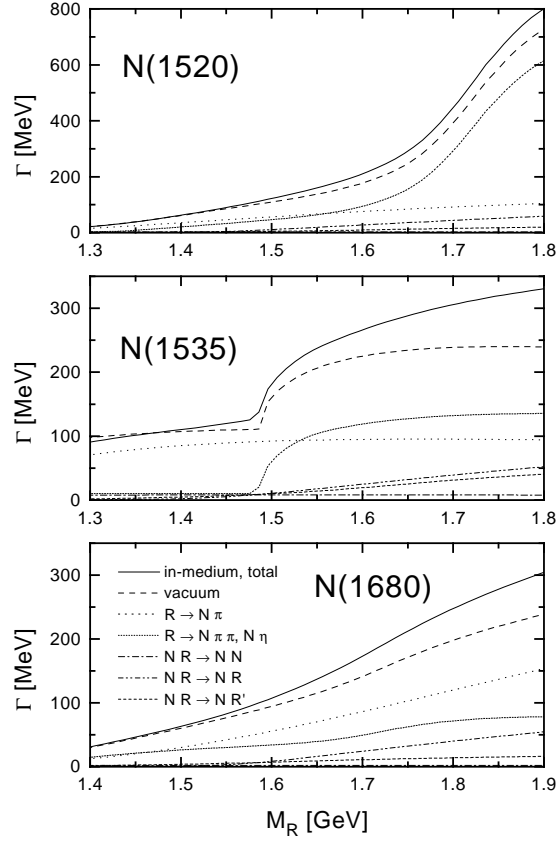


Figure 2: In-medium widths of the higher resonances that are relevant for photonuclear processes.

- The vacuum width appearing in the resonance propagators is replaced by the in-medium width from section 3.
- The collision width gives a Breit-Wigner type contribution to the absorption cross section¹⁴.
- For the Δ -resonance the difference between nucleon and Δ -potential causes a real part of the self energy Π to be used in the resonance pro-

pagator:

$$\text{Re } \Pi = 2 E_{\Delta} (U_N - U_{\Delta}) \quad . \quad (3)$$

- Nucleon final states can be Pauli blocked.

5 Results

5.1 Photoabsorption

Figure 3 shows the total photonuclear cross sections on ^{40}Ca that result from successive application of the medium modifications. Fermi motion alone leads to a damping of the Δ -peak by about $100 \mu\text{b}$ per nucleon. The structure in the region of the D_{13} -resonance is washed out but does not disappear. The peak of the F_{15} -resonance vanishes. Pauli blocking further decreases the Δ -peak by about $100 \mu\text{b}$ with the reduction of the cross section getting smaller at higher energies.

In these calculations the Δ 's experience the same potential as the nucleons. If we apply a Δ -potential of $U_{\Delta} = -30 \rho/\rho_0 \text{ MeV}$ the Δ -peak is shifted to higher energies and decreased by about $70 \mu\text{b}$ per nucleon because the Δ -width increases strongly with increasing mass and the Δ -peak is proportional to $\frac{1}{T}$. Since the position of the Δ -peak becomes density dependent the integration over the volume of the nucleus leads to a further smearing out.

Compared to the experimental data³ we see from figure 3 that we underestimate the cross section in the high mass Δ -region and overestimate the cross section in the region of the D_{13} -resonance. The discrepancy in the Δ -region can be resolved by inclusion of the two-body absorption process $\gamma N N \rightarrow \Delta N$ in our calculations¹⁴.

In figure 3 (lower part) we also show the different contributions to the total cross section. Here we see that the rise of the cross section between 550 and 700 MeV is not only caused by the excitation of the D_{13} -resonance but also to a large extent by the opening of the two-pion background channel. The contribution of the one-pion channel shows almost no resonant structure in this energy regime.

We also calculated the photoabsorption cross section on ^{12}C and ^{208}Pb . The peaks at the Δ -resonance and at 700 MeV decrease slightly with increasing mass. The qualitative behaviour of the photoabsorption cross section does not depend on the mass number.

While the collisional broadening can, according to our results, not explain the observed disappearance of the higher resonances, there are other in-medium effects that still have to be explored. For example, there is the possibility that the width of the D_{13} -resonance is increased by a strong medium

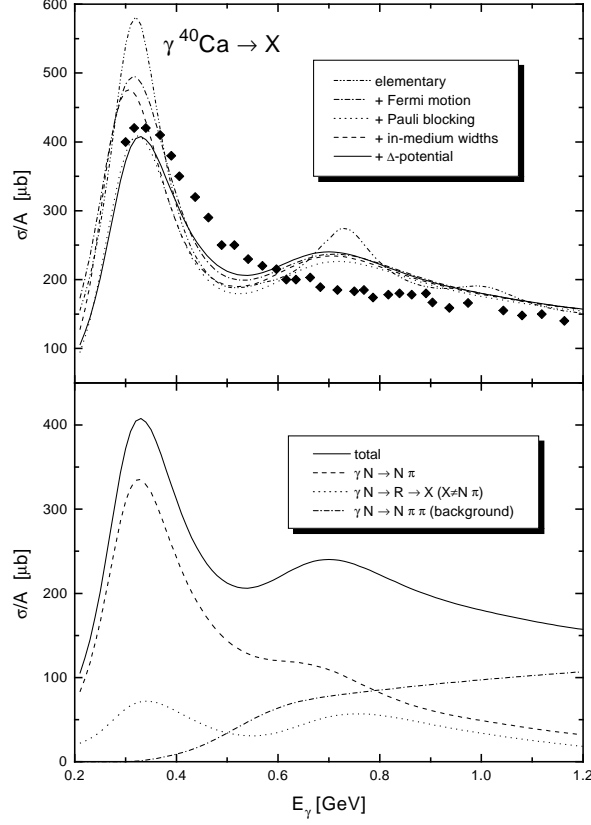


Figure 3: Photoabsorption cross section on ^{40}Ca . The experimental data are obtained by an average over different nuclei³.

modification of the free width, for example caused by the strong coupling to the $N\rho$ -channel and a downward mass shift of the ρ -meson in the nuclear medium¹⁸. This may lead to the disappearance of the structure in the region of the D_{13} -resonance. Another possibility is a strong medium modification of the elementary $\gamma N \rightarrow N\pi\pi$ cross section in the nuclear medium or a medium effect on the background amplitudes.

An understanding of the disappearance of the D_{13} -resonance in the photoabsorption cross section might thus be possible by a comparison between

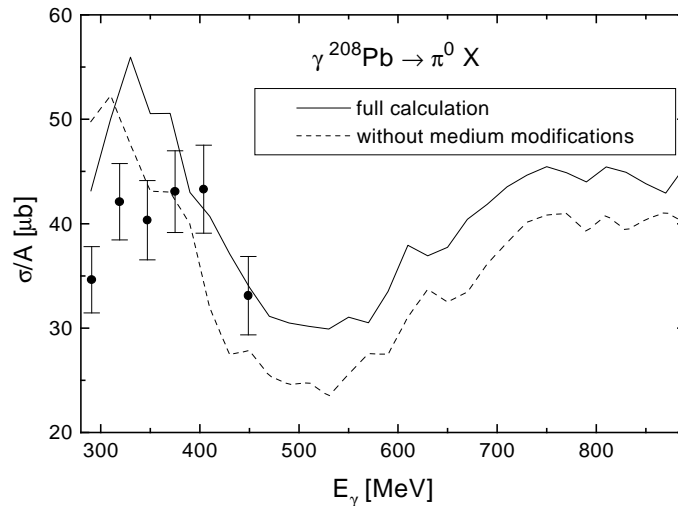


Figure 4: Total π^0 photoproduction cross sections on ^{208}Pb . The experimental data are taken from ¹⁹. The fluctuations in the calculated curves are caused by low statistics.

theory and experiment with respect to more exclusive reaction channels.

5.2 Pion production

The total π^0 cross section on ^{208}Pb is shown in figure 4 ¹⁴. The curve labeled 'without medium modifications' results when applying only Fermi motion and Pauli blocking and neglecting the difference between nucleon- and Δ -potential and the in-medium widths of the resonances. The difference to the full calculation is basically caused by the Δ -potential. In the region of the Δ -resonance the elementary absorption cross section is reduced and shifted to higher energies ¹³. For larger photon energies the Δ -potential leads to a slight enhancement of the pion production due to its effect on the pion-nucleon interaction. Compared to the experimental data ¹⁹ our calculation overestimates the cross section in the region of the Δ -resonance by about 20% and we fail to explain the broad structure in the Δ -region. The same holds for calculations on ^{12}C ¹⁴.

The discrepancy in the Δ -region might be due to a further reduction of the cross section for $\gamma N \rightarrow N \pi$ in the nuclear medium. A better description of the total photoabsorption cross section then certainly requires the inclusion of two- and three-body absorption mechanisms for the photon. This may also lead to a better description of the observed structure of the cross sections.

5.3 *Eta production*

We have parameterized the etaproduction on the free nucleon under the assumption that the only production mechanism is via an intermediate $N(1535)$ -resonance¹⁴. In nuclei we also have to take into account eta production by final state interactions of pions that were primary produced.

In figure 5 we compare the calculated total etaproduction cross section on ^{12}C , ^{40}Ca and ^{208}Pb with experimental data²⁰. The contributions coming from secondary processes are almost negligible. For large photon energies our calculation depends on the choice of the elementary $\gamma N \rightarrow N \eta$ cross section for photon energies larger than 800 MeV because of the Fermi motion of the nucleons. An extrapolation of this cross section according to low momentum transfer electroproduction¹⁴ reduces the total cross section at 800 MeV by about 15% and gives a better description of the experimental data. On ^{12}C there is only good agreement with the experiment at low photon energies. For higher energies we overestimate the cross section by about 20%. On ^{40}Ca and ^{208}Pb the agreement with the experiment is very good.

6 Summary and outlook

We have presented a calculation of the photoabsorption cross section and cross sections for inclusive pion and eta photoproduction in nuclei within a semi-classical BUU transport model for photon energies from 300 MeV to 1 GeV. Starting from a reasonable parameterization of the free photon nucleon cross section we applied the medium modifications Fermi motion, Pauli blocking and collision broadening for the involved nucleon resonances.

For the $\Delta(1232)$ -resonance it turned out that collision broadening and reduction of the free width by Pauli blocking nearly compensate each other resulting in a very small net broadening. The collision broadening of the higher resonances in our model is almost negligible.

Our calculated photoabsorption cross section fails to describe the experimentally observed disappearance of the D_{13} -resonance. This might be caused by a strong broadening of the D_{13} -resonance in the nuclear medium due to a strong coupling to the $N\rho$ -channel and a mass shift of the ρ -meson in the nuclear medium but also by a medium modification of the $\gamma N \rightarrow N \pi \pi$ process.

In the Δ -region we are able to reproduce the size of the observed pion production cross sections in nuclei reasonably well although our calculated cross sections show too much structure in the resonance region. This might be due to the importance of multi-body absorption mechanisms.

The agreement of the calculated total eta production cross section with

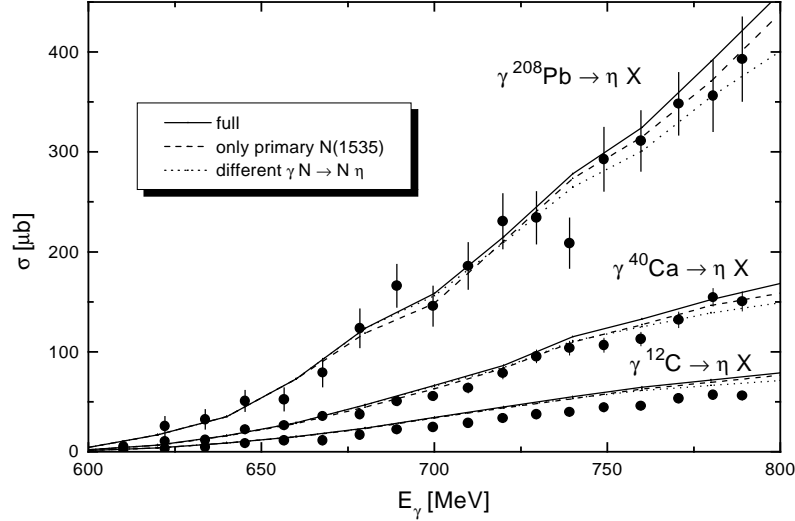


Figure 5: Total eta photoproduction cross section on ^{12}C , ^{40}Ca and ^{208}Pb . All experimental eta photoproduction data are taken from ²⁰.

the experiment is good.

An experimental measurement of exclusive cross sections would be helpful for a better understanding of the photon-nucleus reaction and an explanation of the disappearance of the D_{13} -resonance in the total photonuclear absorption cross section. In particular, the experimental investigation of the 2π -channel on nuclei would be very important because of the opening of this channel in the $N(1520)$ -resonance region.

Acknowledgments

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References

1. T. Frommhold et. al., Phys. Lett. **B295** (1992) 28.
2. N. Bianchi et al., Phys. Lett. **B299** (1993) 219.

3. N. Bianchi et al., Phys. Lett. **B325** (1994) 333.
4. N. Bianchi et al., LNF-95-053-P (1995), Phys. Rev. **C** in press.
5. M. MacCormick et al., Phys. Rev. **C53** (1996) 41.
6. T. A. Armstrong et al., Phys. Rev. **D5** (1972) 1640.
7. T. A. Armstrong et al., Nucl. Phys. **B41** (1972) 445.
8. G. F. Bertsch et al., Phys. Rev. **C29** (1984) 673.
9. W. Cassing et al., Phys. Rep. **188** (1990) 363.
10. Gy. Wolf et al., Nucl. Phys. **A552** (1993) 549.
11. S. Teis et al., Z. Phys. **A356** (1997) 421.
12. A. Engel et al., Nucl. Phys. **A572** (1994) 657.
13. M. Effenberger et al., Nucl. Phys. **A613** (1997) 353.
14. M. Effenberger et al., Nucl. Phys. **A614** (1997) 501.
15. L. A. Kondratyuk et al., Nucl. Phys. **A579** (1994) 453.
16. W. M. Alberico et al., Phys. Lett. **B321** (1994) 177.
17. R. A. Arndt et al., Phys. Rev. **C42** (1990) 1853.
18. M. Rho, Int. Conf. Nucl. Phys., Beijing, 1995, nucl-th/9508046.
19. J. Arends et al., Nucl. Phys. **A454** (1986) 579.
20. M. E. Röbiger-Landau et al., Phys. Lett. **B373** (1996) 45.